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Marston, Philip L.

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Physics and Astronomy Department
Washington State University
Pullman, WA 99164-2814

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Email address: marston@wsu.edu   Telephone Number: 509-335-5343

14. ABSTRACT
Sound incident on the sea bottom at small grazing angles can produce acoustical evanescent waves in the sediment. The objective of this project was to describe the scattering by regular and irregular objects illuminated by acoustical evanescent waves in a simulated sediment. The theoretical developments were tested with laboratory scale experiments using a unique facility. The observables of interest in the scattering included (but were not limited to): (a) the scattering amplitude as a function of target depth and orientation; (b) the timing of the scattered signals; (c) the frequency dependence of the scattering. Objects investigated included objects having narrow resonances. The results should be helpful in selecting filters to optimize the signal-to-reverberation-ratio for targets buried in real environments and to reduce the rate of false alarms.

15. SUBJECT TERMS
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Final Technical Report for Office of Naval Research grant N00014-03-1-0585

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Philip L. Marston, Principal Investigator
Physics and Astronomy Department, Washington State University,
Pullman, WA 99164-2814
Phone: (509) 335-5343, Fax: (509) 335-7816, E-Mail: marston@wsu.edu

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I. Summary

The purpose of this investigation was to improve the understanding of the way that acoustic evanescent waves interact with targets buried in sediments in situations encountered in underwater acoustics. A method was developed and tested for the stable laboratory production of acoustic evanescent waves in water based on the reflection of a beam of sound at an interface between the water and an adjacent liquid. The evanescent wavefield was measured and it was modeled using the wave-number integration code OASES. Responses of targets illuminated by this evanescent wavefield were measured and the major features were modeled. The emphasis was on backscattering from cylindrical targets having strong resonances. Some of the most important observations are: (1) the strong dependence of the backscattering on the cylinder location relative to the interface (that is, the effective burial depth of the cylinder), and (2) the strong dependence of the backscattering on the orientation of the cylinder.

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II. Introduction

ONR Grant N00014-03-1-0585 "Scattering of Evanescent Acoustic Waves by Regular and Irregular Objects" was through the program originally designated Code 32MIW for research described in a proposal submitted in 2002. Eventually the supporting program was designated the ONR MCM Sensors Program. By agreement with ONR, one of the graduate students participating in this effort (Curtis F. Osterhoudt) was initially supported by an ONR Graduate Traineeship grant (N00014-03-1-0262). That grant did not include operations costs for the experiment and the related facility costs. Following the depletion of salary funds from the Traineeship grant, the salary for Osterhoudt was shifted to N00014-03-1-0585 and currently to the follow-on grant (N00014-06-1-0045). As explained in Section II the nature of the experiment was such that at any given time more than one graduate student was typically involved and at times undergraduate students have also been involved. In additional, because of certain laboratory and computational demands of the project at times partial support has been provided at the Post-Doctoral level to a research faculty member.

The effective speed of sound in sediments typically exceeds the speed of sound in the water column above and this has some important consequences. For example the typical speed of sound in the water and in the sediment are $c_w = 1536$ and $c_b = 1770$ m/s, respectively. The corresponding critical grazing angle α_c is arccos(1536/1770) = 29.8° (which corresponds to a critical angle of incidence relative to the normal of $\theta_c = 90 - \alpha_c = 60.2°$). Neglecting the attenuation of sound in the sediment and in the water column gives the well-known prediction that: (1) plane waves incident with grazing angles $\alpha < \alpha_c$ are totally reflected and (2) for such waves the acoustic amplitude decays exponentially with increasing depth in the sediment. The associated exponentially decaying wavefield in the high-speed medium (the sediment) is commonly referred to as an evanescent wave or an "inhomogeneous" wave. While real sediments can have significant attenuation and often have non-smooth surfaces, there is considerable evidence for the existence of an evanescent nature of the transmitted sound and of the associated complications of using sound with *post-critical incidence* (grazing angles with $\alpha < \alpha_c$) for the detection of buried objects. (The following comment on terminology may be helpful: while in *optics* the angle of incidence θ relative to the normal is often used to specify the incident direction, in *underwater acoustics* most recent authors use the grazing angle so that the idealized total-reflection region is associated with "subcritical" incidence. To avoid confusion, the term "post-critical" incidence is used here.) There is evidence that diffraction by *ripples* on the sea floor frequently alters the post-critical reflection and transmission of sound. It has been reported, however, that even with moderate ripples, conditions below about 6 kHz can be found *at sea* where the dominant transmitted wave is an evanescent wave. Furthermore, it is expected, the ripple effect is lessened when the seafloor is viewed in a direction generally parallel to the ripples. It is frequently desirable to view the bottom acoustically from the greatest possible distance which means that the grazing angle is small and post-critical conditions apply. For this reason it is highly desirable to gain an improved understanding of the description of the scattering of sound by evanescent waves for both man-made and natural objects. **Figure**

1 illustrates an example of the situation. The complications introduced by evanescence on the acoustic detection and classification of buried objects is the topic of research in this project.

The report given here summarizes progress as of the termination of the grant on 30 Sept. 2006. Details and some additional progress will be described in Osterhoudt's Ph. D. dissertation which is in preparation [1]. Related research using a different type of target is being studied by a different Ph. D. candidate graduate student (Aubrey Espana) supported by the follow-on grant (N00014-06-1-0045).

While it is not separately reported here, to facilitate the proper characterization of targets used in (or considered for) evanescent wave experiments, funds from this grant partially supported improvements to the scattering facility based on ordinary propagating acoustic waves carried in a 6000 gallon tank. Some of those improvements were noted in the Annual Report Submitted in September 2006 [2].

III. Laboratory Method for Generating Acoustic Evanescent Waves

At the time this grant started in 2003 there was no widely recognized standard approach for the laboratory generation of acoustic evanescent waves. Consequently various approaches were examined during the first grant year. While testing various combinations of liquids, a research faculty member having a background in chemical engineering (Dr. David B. Thiessen, who was partially supported by this grant) discovered a suitable liquid mixture having the required sound-speed, density, and safety properties. This environmentally-friendly liquid mixture, when placed in contact with water, has the desirable acoustic contrast to facilitate the production of acoustic evanescent waves in water. The mixture does not mix with water. It is denser than water and has a 885 m/s sound speed. The low velocity liquid is in a 70 gallon tank surrounded by water in a 3000 gallon tank, **Figure 2**. The low velocity liquid is a mixture of HFE-7500 manufactured by 3M Corporation with 5 cS kinematic viscosity PDMS silicone oil. This system is used to generate wavefields having significant evanescent components by illuminating the interface with a beam having post-critical incidence. The source transducer is placed in the dense liquid mixture, which simulates the ocean water column. The water in the tank above the mixture simulates the ocean bottom. The typical operating frequency used is 60 kHz in a tone-burst mode of operation. The evanescent wavefield decays upward in the water since the simulated water column (the oil) is denser than (and is trapped below) the simulated water column (the water). This is a convenient arrangement since it allows hydrophones and target positions to be easily scanned within the simulated bottom. This system of liquids is more suitable for long-term indoor use than the vegetable-oil/glycerin system used in related studies by a group at a Naval facility. The disadvantage of our system is the high cost of the liquids used in the mixture. In 2005 the price of the ingredients in the HFE-oil mixture was such that the cost of the mixture was approximately $175 per gallon. In most experiments it was necessary to use coherent background subtraction in which a background signal is recorded in the absence of a target and that signal is subtracted from the record when the target is present to infer the scattering.
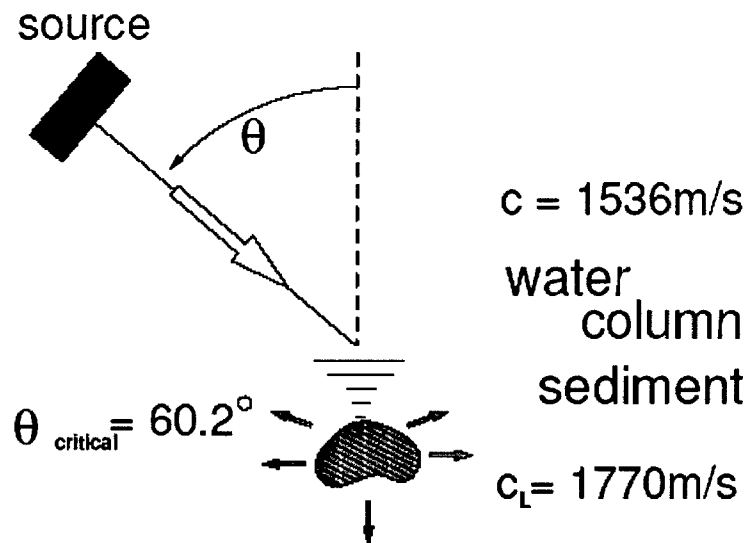
Figure 1. Generic problem associated with detecting objects buried in sediments with a sound source at grazing incidence. When the angle of incidence θ is larger than the critical angle $\theta_{critical}$ for some conditions the transmitted acoustic wavefield decays exponentially with depth in the sediment even when absorption by the sediment is weak. Furthermore the exponential decay rate increases the larger the value of $(\theta - \theta_{critical})$. The acoustic wave associated with this exponential decay is an evanescent wave.
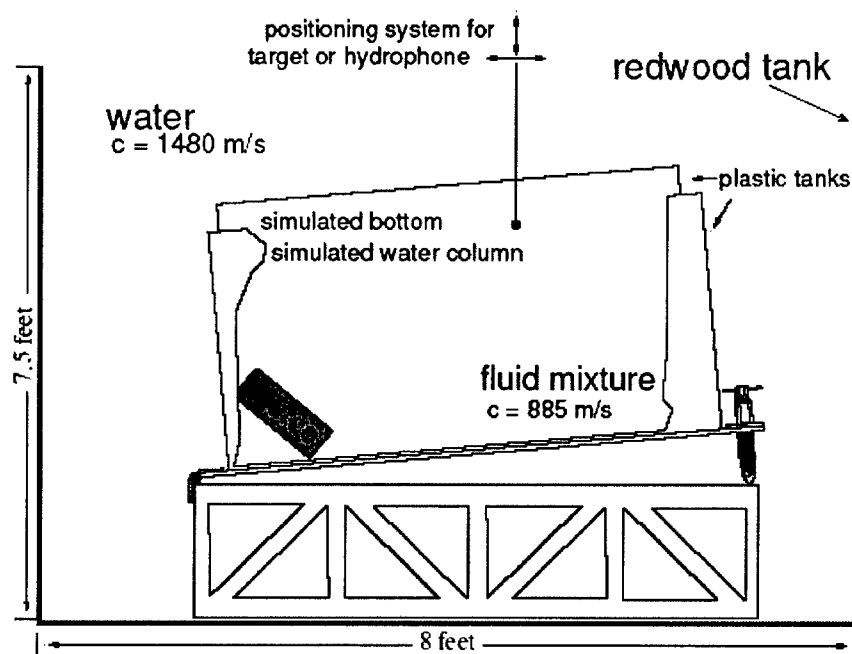
Figure 2. Main features of the apparatus for studying the acoustical scattering.

Installing the appartus shown in Figure 2 required significant modification of one of the existing water tanks. The manpower requirements for that task and for the installation and alignment of experiments is one of the reasons that at times multiple students were involved. Positioning systems were procured (or in some cases modified from an existing system) to facilitate target movement and adjustment of target orientation. In addition, a positioning system was installed to move the hydrophone.

IV. Modeling of the Acoustic Evanescent Wavefield with OASES

A well-known wave-number integration code for wavefield calculations is the OASES code developed at MIT by H. Schmidt. Though the available version of the code could not provide a full simulation for the geometry considered in Figure 2, it was possible to provide a partial simulation. Initially these simulations were supported in part by ONR SWAMSI grant N00014-04-1-0075 which included some supplemental support to facilitate assistance by Associate Professor Scot F. Morse (Computer Science Department, Western Oregon University). Subsequently OASES based simulations were carried out entirely at WSU with support from grant N00014-03-1-0585 and the Traineeship grant (N00014-03-1-0262).

The comparison of measured and modeled wavefields was reported at the May 2005 and October 2005 meetings of the Acoustical Society of America [3,4]. Scans of the wavefield in the simulated sediment reveal the fine structure and interference features of the total incident wave. The wavefield in the simulated sediment can exhibit complicated nulls associated with the interference of algebraic and exponentially decaying wavefields. We found similar nulls in the wavenumber integration (OASES-based) simulations. We also predicted the spacing of the nulls [1] by extending the approach of Matula and Marston [5]. A measured 60 kHz wavefield and the wavenumber-integration based simulation in the simulated sediment (the water) were found to have similar features [1]. This comparison is archived in the on-line version of the 2005 Annual Report for the Traineeship grant [6].

V. Target Selection for Studying Resonances Excited by Evanescent Waves

To assist in MCM applications related to objects buried in sediments, it was decided to examine the scattering by objects having sharp or "high-Q" modes. The emphasis was on cylindrical objects. We mostly studied high-Q modes of water-filled hollow metal cylinders. These modes are related to ones previously examined by Hackman [7] for solid cylinders. These modes were studied by Osterhoudt and Marston [8] for water-filled cylinders excited by ordinary propagating waves. In our model for the scattering of sound by cylinders illuminated by ordinary waves, the high-Q of this "organ pipe mode" of the water filled cylinder is the result of the internal reflection coefficient being close to unity [8].

In our experiments the cylinder is illuminated by evanescent waves generated using the apparatus shown in Figure 2. The backscattering to the source transducer is recorded as a function of the distance of the cylinder-end from the oil-water interface.

For many of the experiments the cylinder's axis was perpendicular to the interface. As described in the Annual Report for 2004 [9] the initial experiments were with a small solid brass cylinder having a resonance at 111 kHz. By the time of the Annual Report for 2005 [10] we were studying the high-Q modes of small water-filled hollow stainless steel cylinders. **Figure 3** shows an example of a time record for backscattering by a cylinder placed close to the interface. The figure shows the build up of the response of the mode followed by the exponential decay of the cylinder oscillations. The cylinder is driven by a 64 kHz tone burst. This signature is only present when the frequency of the tone burst is close to a resonance frequency of the target.

VI. Position Dependence of the Backscattering with a High-Q Resonance

One of the objectives of this research was to understand how the scattered signal varies with the effective target depth for the case of evanescent wave illumination. Our measurements with a vertical water-filled hollow stainless steel cylinder revealed an important surprising behavior. Prior work by Matula and Marston [11] on the diffraction by a sharp metallic edge illuminated by an evanescent wave in air showed that the *near forward* diffraction decayed exponentially with target position at the same rate as the exponential decay of the incident evanescent wave. The surprising result from our recent measurements was that the backscattering to the source transducer decays at nearly twice the spatial rate as the exponentially decaying incident wave. This is modeled below. **Figure 4** illustrates this result. The crosses show the natural-log of the peak backscattered pressure when the cylinder is driven close to resonance by a 25 cycle tone burst. The circles show $[2 \, Ln(p_h)] + B$ where p_h is the measured hydrophone pressure when the hydrophone is scanned vertically through the incident wave and B is a constant related to an amplitude scale factor. Note that in order to obtain agreement in the spatial decay rates it was essential to include a scale factor for $Ln(p_h)$ at (or close to) 2. This means that the spatial decay rate for the backscattering is approximately twice that of the incident wavefield. If the spatial dependence was purely exponential, of the form $\exp(-A_n z)$, where A_n is a constant and z is the distance from the interface, then the data would give a straight line in **Figure 4**. The slight curvature is associated with non-evanescent components of the incident wavefield attributable to the finite size of the transducer. (The curvature is present because the wave incident on the oil-water interface is not a true plane wave.)

VII. Burial-Depth Dependence of the Backscattering Amplitude from Reciprocity

Our theoretical argument for the behavior shown in **Figure 4** is based on reciprocity and an assumption that the excitation of (and radiation by) the target causing the backscattering is localized to a small region of the target. Suppose that the one-way transmission from the source to that point is proportional to the function: $|p_i| = F_a F_e$ where F_a is an algebraic (slowly varying) function of target position and F_e is an exponential (or approximately exponential) function of target position. For example, if z denotes the distance of the relevant coupling point from the interface, then for purely
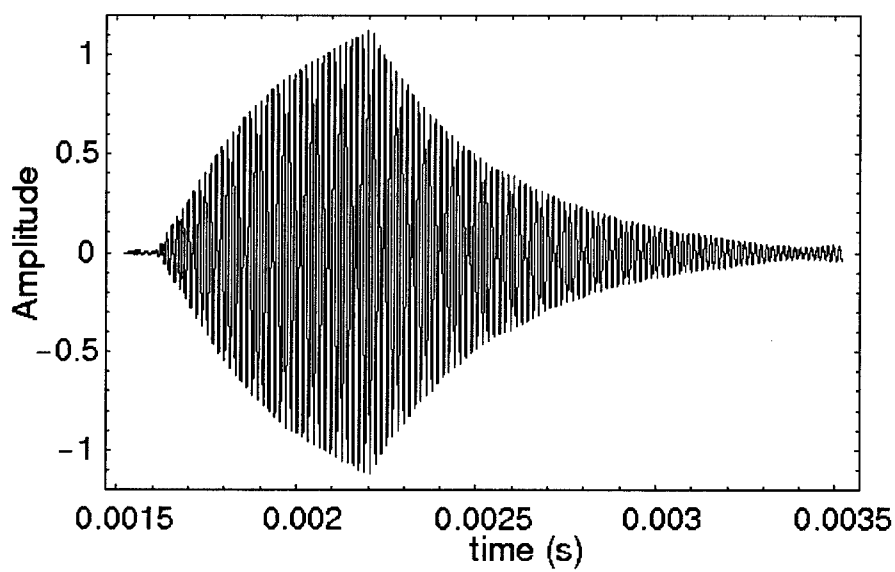
Figure 3. The signal scattered from the target back to the source when a horizontal water filled cylindrical shell is driven by a 64 kHz evanescent wave. Here, the target's lowest organ-pipe mode is strongly excited, and a ring-up is followed by a gradual decay.
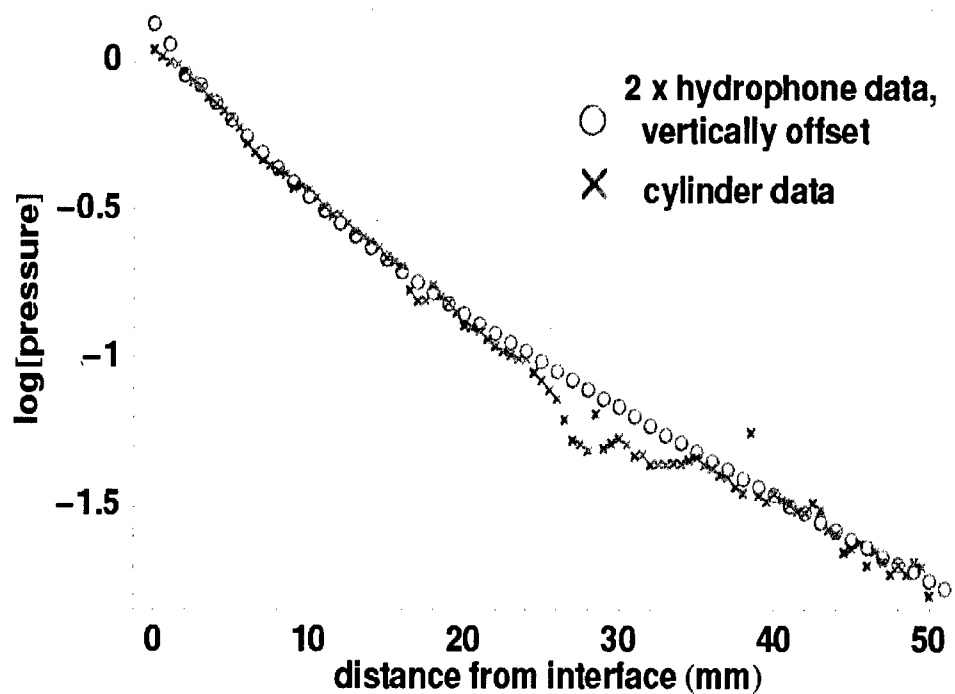
Figure 4. Comparison of measured backscattering by a vertical cylinder and rescaled wavefield data.

evanescent excitation, $F_e = \exp(-A_1 z)$ where A_1 is the exponential *spatial* decay rate of the incident wave. From reciprocity it is expected that the backscattering amplitude will be proportional to the following product: $|p_b| \propto |p_1|^2 = F_a^2 F_e^2 = F_a^2 \exp(-2A_1 z)$ where $\exp(-2A_1 z) = \exp(-A_2 z)$ with $A_2 = 2A_1$. (Here the symbol "$\propto$" means "Is proportional to...") This "double-rate" decay behavior is a new result not predicted explicitly by prior publications on scattering by buried targets. This result, if generalizable to other situations, has profound implications for the detection of mines buried below smooth interfaces. A partial analogy to this doubly-strong behavior was recently reported by Dzikowicz and Marston [12] where it was found that small targets at the focus of a curved surface exhibited doubly-strong focusing in backscattering for reciprocal paths connecting the source, curved surface, and the target.

VIII. Progress During Fiscal Year 2006

During Fiscal-Year 2006 the progress was mainly in the following four areas: (1) Facilities improvements needed to improve our ability to make low-frequency-free-field scattering measurements; (2) Evanescent wave excitation of organ pipe modes of horizontal water-filled cylinders; (3) Finite-element models of evanescent wave coupling to cylinder modes; and (4) Identification of low-frequency modes of other targets. This research was summarized in the Annual Report for 2006 [2] which is reproduced here in a slightly modified form as **Appendix A**. The most important result was the investigation of the dependence of the backscattering of an evanescent wave by the horizontal cylinder on the tilt angle of the cylinder [13]. Some other progress in 2006 included the investigation of how the quality factor (Q) of a horizontal water-filled cylinder depends on the distance from the interface. That is described in the Annual Report for the Traineeship [14].

IX. Supplemental Research

In support of this project, Marston carried out various exploratory theoretical investigations. The emphasis was on the analysis of the scattering by horizontal cylinders illuminated broad-side by low-frequency evanescent waves [15,16]. An exact partial-wave series was obtained in the infinite cylinder case and the exact results were compared with different types of approximations. Marston also constructed the exact partial-wave series for the scattering by a spherical target centered on a Bessel beam [17]. The series is sufficiently general to allow for the special case of an evanescent wave Bessel beam in which the beam decays exponentially fast along the beam axis. In addition some overviews of scattering processes were written and published [18,19].

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XI. Appendix A: Annual Report Submitted for Fiscal Year 2006

Scattering of Evanescent Acoustic Waves by Regular and Irregular Objects

Philip L. Marston
Physics Department, Washington State University
Pullman, WA 99164-2814
phone: (509) 335-5343   fax: (509) 335-7816   email: marston@wsu.edu

LONG-TERM GOALS

When sonar is used to search for mine-like objects buried in sand, it is important to understand the coupling of the incident sound with targets of interest. For grazing incidence, in certain frequency ranges there is evidence that the incident wave in sand can have an important evanescent component. The long-term goal is to determine the consequence of the evanescence of an incident acoustic wave on the properties of scattered sound. The model targets of interest include potential background targets as well as mine-like targets.

OBJECTIVES

The main objective this year was to improve our measurements and understanding of the scattering of sound by scaled targets when the incident wave is an acoustic wave having significant evanescent components. The consequences of incident-wave evanescence are being examined for some existing and under-utilized scattering observables. This research should be helpful for discriminating between echoes of real buried targets and background objects. To assist in the aforementioned long-term goal, some additional theoretical consequences of evanescence on the scattering by buried cylindrical targets are being explored that are not related to current observations.

APPROACH

Simulation tank experiments are being carried out. We previously identified an environmentally-friendly liquid mixture that, when placed in contact with water, has the desirable acoustic contrast to facilitate the production of acoustic evanescent waves in a tank having a substantial volume. The mixture does not mix with water and is denser than water and typically has a speed of sound of 885 m/s. Approximately 70 gallons of the dense liquid are placed in an inner tank surrounded by a 3000 gallon water tank. This system was used to generate wavefields having significant evanescent components by illuminating the interface with a beam having post-critical incidence. The source transducer is placed in the dense liquid mixture, which simulates the ocean water column. The water in the tank above the mixture simulates the ocean bottom. Backscattering is measured by switching the source transducer to a receive mode. Elsewhere we

demonstrated that several detailed features of the generated wavefield were in agreement with calculations from a wavenumber-based simulation [1,2] and we described preliminary measurements of the scattering by small cylinders [3,4]. The incident wave involves a superposition of an evanescent wave and diffracted waves associated with the finite size of the source transducer. We previously noted a surprising result for vertical cylinders driven at resonance: the measured backscattering decays with increasing distance from the interface at nearly twice the spatial rate as the exponentially decaying incident wave [4]. This enhanced decay was explained using reciprocity.

Professor P. L. Marston directs the research. C. F. Osterhoudt and A. E. Espana are Ph. D. candidate graduate students participating in this research. C. Dudley (a graduate student now supported by a different ONR grant) provided assistance during part of the year. Dr. D. B. Thiessen provided part-time computational assistance.

During FY-2006 the grant activities include: (1) Facilities improvements: This was needed to improve our ability to make low-frequency-free-field scattering measurements of targets considered for use in evanescent wave experiments. Other aspects of these improvements are described elsewhere [5,6]. (2) Evanescent wave excitation of organ pipe modes of horizontal water-filled cylinders: We previously described how these sharp high quality factor (high Q) modes could be excited for a vertical cylinder. The emphasis in FY 2006 was on studying horizontal cylinders. (3) Finite-element models of evanescent wave coupling to cylinder modes: This was primarily the work of Thiessen. (4) Identification of low-frequency modes of other targets: Espana has been studying the free-field response of small targets potentially suitable for evanescent wave experiments. (5) Related theoretical developments: In addition to activities (1)-(4) there has been other analytical progress on modeling the response of targets to evanescent waves. This will not be separately summarized.

WORK COMPLETED

The accomplishments are outlined below in the Results section. The most significant discovery is that the backscattering from a horizontal cylinder driven in a high Q mode has a different dependence on tilt angle than for a free-field cylinder illuminated by non-evanescent waves.

RESULTS

For the activities listed in the Approach section the results are summarized below:

(1) Facilities improvements: Some results enabled by improvements are noted below.

(2) Evanescent wave excitation of organ pipe modes of horizontal water-filled cylinders: Our previous result for a vertical cylinder (driven in a high Q mode) that the measured backscattering decays (with increasing distance from the interface) at nearly twice the spatial rate as the exponentially decaying incident wave was experimentally found to also occur for broadside evanescent illumination of a horizontal cylinder also driven in a high

Q mode. A model which explains this behavior was developed based on reciprocity. Another significant discovery concerns the tilt angle dependence of the backscattering from a horizontal cylinder driven in a high-Q mode by an evanescent wave. The backscattering has a different dependence on tilt than calculated for a free-field cylinder illuminated by non-evanescent waves. The important geometrical aspects of the measurement are shown in Figure A1. A small cylinder is hung entirely in the water to simulate a cylinder completely buried in sediment. The length and outside diameter of the cylinder are 10.4 mm and 2.1 mm. A source and receiver transducer in the oil is taken to be located in the plane of the figure outside the field of view. The source is excited with a 64 kHz tone burst. The frequency was selected to excite the lowest organ-pipe mode of the open-ended cylinder. The angle of incidence θ (theta) of the beam is such that the beam is totally reflected in the absence of the cylinder [1,2]. Though the cylinder remains horizontal the tilt angle may be varied. The angle is denoted by γ (gamma) in Figure A1 where a value of 90 degrees denotes broadside illumination by the evanescent wave and a value of 0 denotes end-on illumination. In a typical measurement the cylinder is a small fraction of a wavelength from the interface. By driving the lowest organ-pipe mode at resonance and by fitting the build-up of the target's oscilloscope record, a measure of the steady-state amplitude is obtained. Examples of time-signatures are shown in last year's report [4] and this year in a separate report [7].

Figure A2 shows the measured and modeled response as the tilt is varied for the conditions previously noted. The backscattering amplitude is extracted by fitting the initial rise of the echo amplitude using a signature model in which the scattering is dominated by a single mode of the target. The amplitude decreases away from broadside illumination in a way that is approximately consistent with a simplified model (the smooth curve) that takes into account the evanescent nature of the illumination. The model of the angular dependence assumes a single mode dominates the scattering and that the cylinder is horizontal and close to the interface [8,9]. Elementary consideration of the effect of perspective on non-evanescent coupling predicts a weaker dependence on the tilt for the case of illumination by an ordinary wave.

(3) Finite-element models of evanescent wave coupling to cylinder modes: Since there have been few general numerical approaches to computing the coupling of acoustic evanescent waves with the modes of a buried target, a finite element approach was explored. This was done for the symmetric coupling configuration described in the report for FY 2005 [5]. That report emphasized the coupling to the organ-pipe mode of a vertical water-filled cylindrical shell. To demonstrate coupling in that case using finite elements, a vertical cylindrical shell (taken to be rigid walled) having open ends as in the experiment is positioned along the vertical symmetry axis of the upper computational domain (the water which is the simulated sediment). Acoustic standing wave modes in the oil (the lower fluid in the FEM calculation) were determined for cases where the amplitude decayed in the water (the upper fluid) in the absence of a cylinder. When the cylinder was present, conditions could be found where the evanescent mode in the upper fluid coupled strongly to the cylinder producing large acoustic amplitudes within the cylinder. This computational result is shown in Figure A3. This gave a computational verification of the coupling of evanescent waves to organ-pipe modes.

(4) <u>Identification of low-frequency modes of other targets</u>: Evanescent waves in ocean sediments are likely to be most relevant to buried target detection at frequencies below 10 kHz. Consequently, to facilitate laboratory based simulations it is appropriate to identify low frequency modes of other small targets. Experiments are being carried out with non-evanescent waves in a 7000 gallon water tank. The target sizes are selected to produce resonances between 50 and 200 kHz since evanescent wave production in our simulation facility is suitable in that range. The shapes and materials are representative of objects of interest. Figure A4 shows the example of a backscattering signature of a bluntly truncated solid plastic cylinder driven in the quadrupole mode at 64.5 kHz. The frequency is close to the value predicted for an infinite solid cylinder in water of the same material. The build-up to steady state is followed by an exponential decay. Other low-frequency modes of the plastic cylinder have been identified. This generalizes prior observations for plastic spheres [10] to the case of truncated plastic cylinders.

IMPACT/APPLICATIONS

This research improves the understanding of the acoustic signatures of buried targets and the acoustic discrimination of buried targets from background acoustic scattering.

RELATED PROJECTS

One of the graduate students who assists with this project, C. F. Osterhoudt, was previously supported by a Graduate Traineeship Award N000140310262. That award does not cover the significant materials and supplies costs for an experiment of this type. Grant N000140610045 is a grant for continuation of this type of research that was needed because N000140610045 was scheduled to expire in March 2006.

APPENDIX REFERENCES

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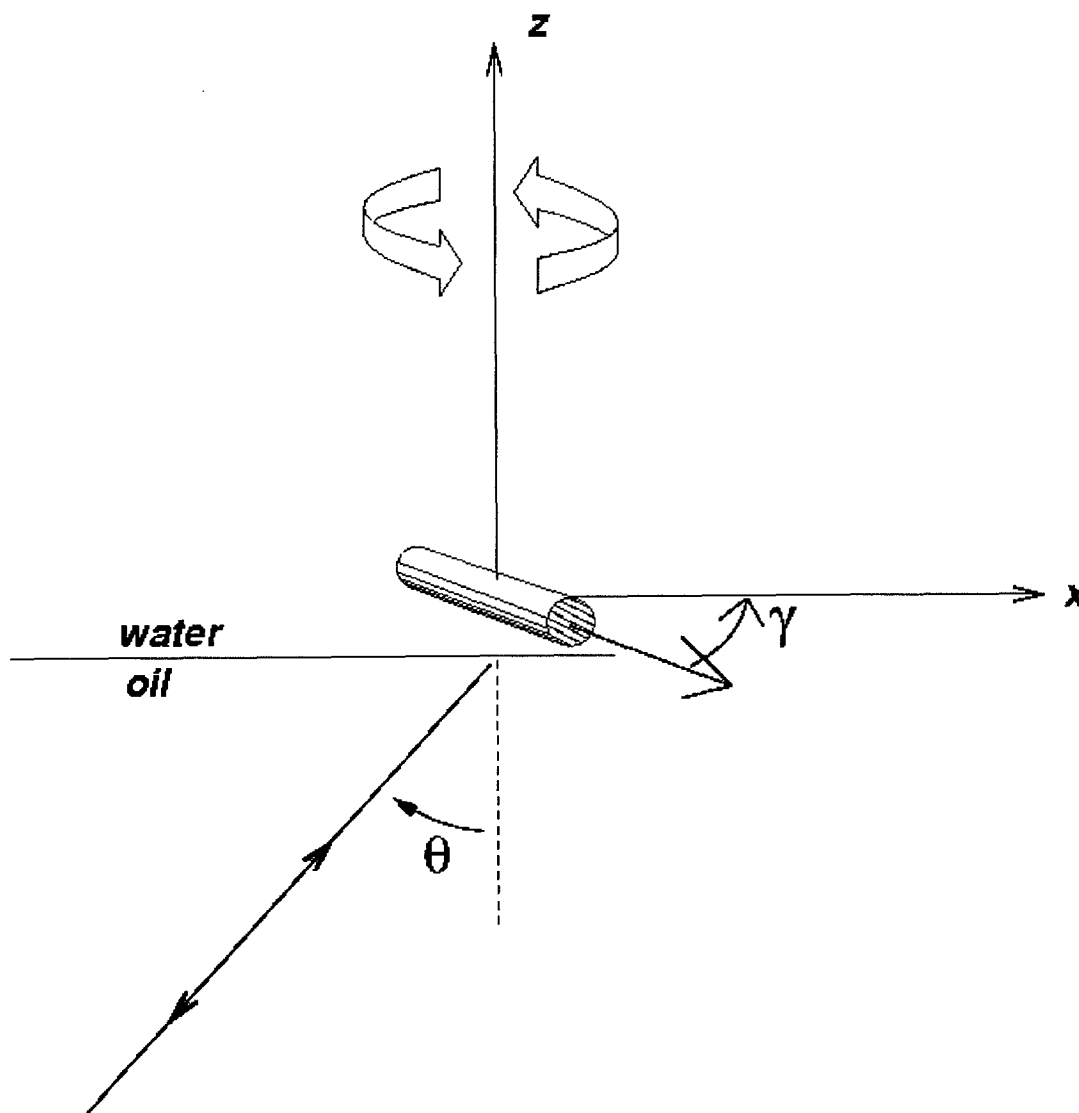
Figure A1. Experimental configuration used to investigate the dependence of the backscattering of an evanescent wave by the cylinder on the tilt angle of the cylinder. The water simulates the sediment and the oil below it simulates the water column in the ocean. A small water-filled stainless steel cylindrical shell is hung above the interface to simulate a buried cylinder. The lowest organ-pipe mode of the open-ended cylinder is excited and the scattering is measured for different tilt angles of the cylinder on a horizontal plane. The angle of incidence at the interface of the incident beam is such that an evanescent wave is generated in the water.
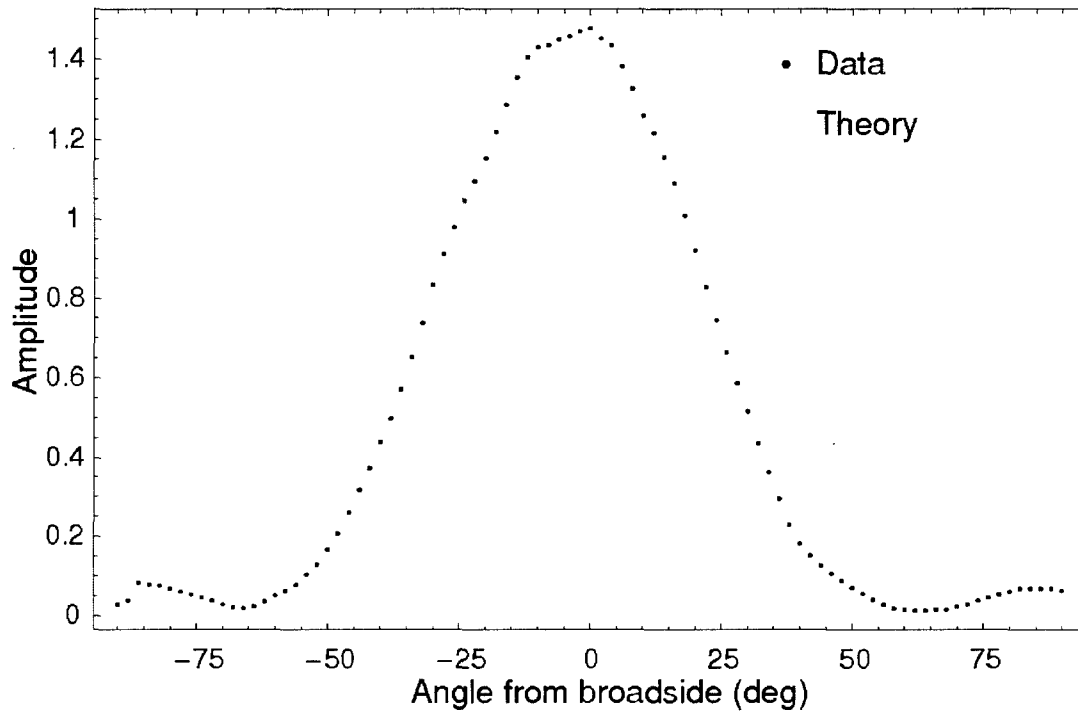
Figure A2. The points are the relative backscattering pressure amplitude determined from measurements with a receiver located at the source. This was done for different tilt angles of the horizontal cylinder using the configuration shown in Figure A1. The horizontal axis is the deviation from broadside illumination. The amplitude decreases away from broadside illumination in a way that is approximately consistent with a model (the smooth curve) that takes into account the evanescent aspect of the illumination. The model assumes a single mode dominates the scattering. The peak amplitude in the model at broadside illumination is adjusted to match the data.
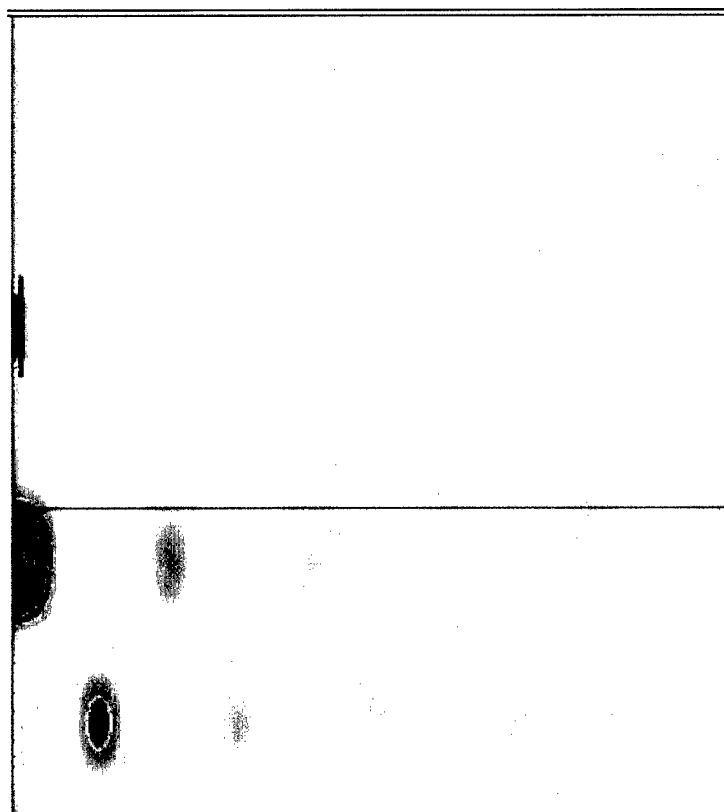
Figure A3. Finite-element model of evanescent wave coupling to a cylinder mode for the geometry investigated in our prior experiments. Low acoustic amplitudes correspond to a turquoise level in the region above the horizontal line that indicates the interface. The propagating mode is in the lower fluid that simulates the water column. The upper computational domain is the water that is the simulated sediment in our experiments. The axis of the cylindrical computational domain is on the left. The color scheme is such that opposite phases give rise to color oscillations in the lower fluid. The axis of the water filled cylindrical shell appears bright red because of the evanescent wave strongly excites the lowest organ-pipe mode of the cylinder. The amplitude in the cylinder is the largest in the computational domain.
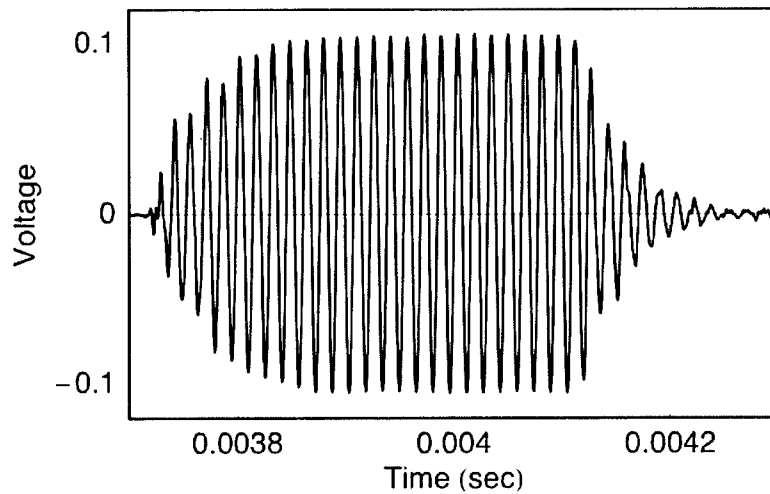
Figure A4. Backscattered echo from a small solid plastic cylinder illuminated by a 64.5 kHz tone burst. The cylinder is positioned to be broadside in the propagating (non-evanescent) incident wave in water. The quadrupole mode of the cylinder is excited. The initial build-up to steady state is followed by the steady response and slow decay of the excited mode. The measurement illustrates a different type of high-Q mode for a small cylindrical target.

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